Interacting X-ray Binaries in Globular Clusters: 47Tuc vs. NGC 6397

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Abstract. Our deep *Chandra* exposures of 47Tuc and moderate exposures of NGC 6397 reveal a wealth of new phenomena for interacting X-ray binaries (IXBs) in globular clusters. In this (late) Review, updated since the conference, I summarize recent and ongoing analysis of the millisecond pulsars, the compact binaries containing white dwarfs and neutron stars, and the chromospherically active binaries in both globular clusters. Spectral variability analysis enables new insights into source properties and evolutionary history. These binary populations, now so "easily" visible, are large enough that their properties and spatial distributions reveal new hints of compact object formation and binary interactions with their parent cluster. Neutron stars appear overabundant, relative to white dwarfs, in 47Tuc vs. NGC 6397. The IXBs containing neutron stars (i.e., MSPs and qLMXBs), as the most massive and ancient compact binary sample, may trace the protocluster disk in 47Tuc, whereas compact binaries may have been ejected preferentially along the cluster rotation equator during the recent core collapse in NGC 6397.

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INTRODUCTION

Globular clusters continue to delight interacting binary afficionados. Whereas only ∼30y ago binaries were virtually unknown in globulars and intermediate mass black holes (IMBHs) were thought to be (e.g. Bahcall and Ostriker 1975) the objects responsible for the population of luminous X-ray sources discovered in 4 globular clusters, compact binaries are now known (e.g. Hut et al 1992) to "rule" the dynamics of globular clusters. Still, it is only now becoming clear with the sharp X-ray eye of *Chandra* just how numerous and interactive compact binaries are when in globular clusters. Not only are there the accreting white dwarfs, or cataclysmic variables (CVs), as the dominant population of low luminosity compact X-ray binaries, as well as the (much) smaller population of quiescent low mass X-ray binaries (qLMXBs) – both originally suspected from the original *Einstein* survey (Hertz and Grindlay 1983) – but also the significant population of primordial binaries containing main sequence (and sub-giant) stars detected by their coronal emission as "active binaries" (ABs). More unexpected was the discovery with the first *Chandra*observation of 47Tuc (Grindlay et al 2001a; herafter GHE01a) that millisecond pulsars (MSPs) are "easily" detected in globulars by their thermal as well as (later recognized for at least 3 of the 19 MSPs with precise locations in47Tuc) non-thermal pulsar wind shock emission. Magnetospheric emission, as from more luminous pulsars, is not generally detected. Other surprises have come from *Chandra* and XMM observations of many other globular clusters (see Verbunt and Lewin 2005 and Verbunt, these proceedings, for recent reviews).

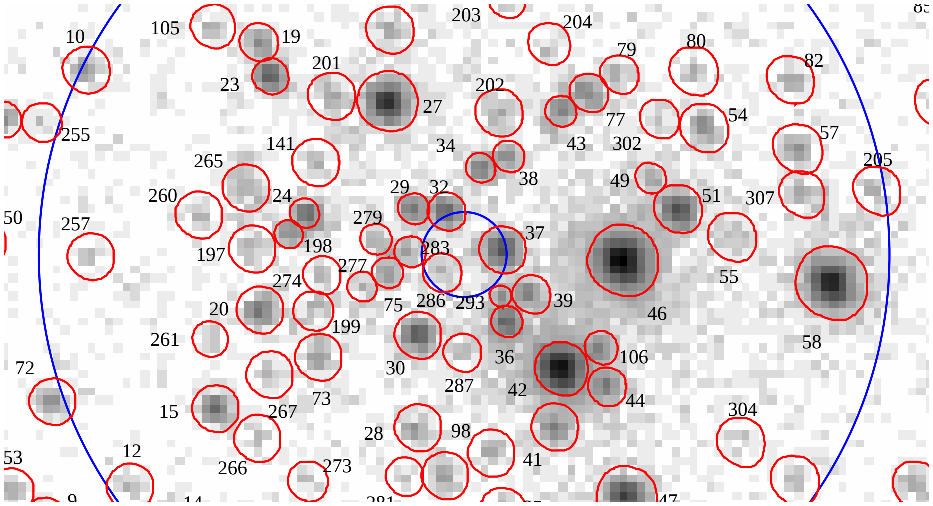

FIGURE 1. *Chandra* image of central region of 47Tuc with circles marking optical core radius (24″) and estimated uncertainty in cluster center position (2.5″). Source W37 is now identified as a qLMXB, leaving only W286 as a contender for a central IMBH.

Here I review the compact binary populations in two particularly interesting, and contrasting, globular clusters, NGC 104 (hereafter 47Tuc) and NGC 6397. I present, or at least touch on, results that suggest the entire suite of low luminosity X-ray sources in globulars – CVs, ABs, MSPs and qLMXBs – are truely interacting X-ray binaries (IXBs), with evidence from each type of source for interactions of the IXB with other cluster members or with the cluster as a whole. Details are given in followup papers.

X-RAY OVERVIEW OF 47TUC

47Tuc remains the "model" globular cluster for a wide range of studies, particularly for IXBs. The very low absorption column $N_H = 1.3 \times 10^{20}$ cm^{-2}allows maximum sensitivity for very soft sources like the thermal emission from the polar caps of MSPs or Polars, and the well-measured cluster dynamics provide a framework for considering sources within the cluster context. Our initial (Mar. 2000) *Chandra* observation (70 ksec, ACIS-I) was presented by GHE01a, and an initial detailed study of the MSPs by Grindlay et al (2002; hereafter GCH02). The rich harvest of IXBs (108 within the central $2.5' \times 2.5'$) merited a deep (4 $\times$65ksec; Oct. 2002) followup with ACIS-S. Initial results and the overall source catalog are presented by Heinke et al (2005a; hereafter HGE05a, and see Heinke, these Proceedings).

New limits for a central IMBH

One of the new results enabled by the first *Chandra* observation of 47Tuc was the first restrictive X-ray limit for the presence of an IMBH in a globular cluster. Thanks to the detection of hot gas in 47Tuc (the *only* globular in which gas has been detected) by

the variable dispersion measure (DM) of its MSPs (Freire et al 2001) and the 0.5$''$ spatial resolution of *Chandra*, the brightest *Chandra* source with position consistent with being at the precise cluster center allowed a IMBH mass limit of 470$M_\odot$ to be derived assuming Bondi-Hoyle accretion with a (low) efficiency ($\varepsilon \sim 10^{-4}$) advection flow (GHE01a). The limiting source within the $\sim$2.5$''$ uncertainty region for the cluster center was source W37, for which the source luminosity was $L_x \sim 1 \times 10^{31}$ erg s^{-1}. This source has since been identified as a probable qLMXB (Heinke et al 2005b; hereafter HGE05b), leaving only source W286 as a contender (W32 is just out of the error circle, but since a IMBH could "wander", it is also a possible candidate and with L_x similar to W37 would yield a similar mass limit; see Fig. 1). The $\sim$10$\times$lower luminosity of W286 reduces by a factor of $\sim$3 the upper limit for IMBH mass (GHE01a),

$$M(IMBH) \lesssim [L_x\,(0.5\text{-}2.5keV)/(4.5 \times 10^{25} \varepsilon_{-4}\, T_{100keV})]^{0.5} \sim 150 M_\odot,$$

where L_x is evaluated in the 0.5-2.5 keV band and is 1.2×10^{30} erg s^{-1}for W286 (HGE05a), ε_{-4} is the advection-accretion efficiency in units of 10^{-4}, and T_{100keV} is the advection-accretion temperature in units of 100 keV. The normalization again assumes the ISM in 47Tuc has density 0.1cm^{-3} as suggested by the DM variations of the MSPs. If the MSP winds have evacuated a bubble in the central core of 47Tuc (note that MSP-W = W29, for which the MSP wind is prominent (see below) is very close to the cluster center), then the IMBH mass limit is correspondingly uncertain.

Millisecond Pulsars: 47Tuc-W is not alone?

The initial *Chandra* observation of 47Tuc showed the MSPs to be predominantly soft thermal sources (GHE01a), with 9 of the 15 then located by radio timing detected and several others plausibly detected. Detailed initial studies (Grindlay et al 2002) of the MSP L_x vs. $\dot{E}$ relation showed a significantly flatter dependence ($L_x \propto \dot{E}^{0.5}$) than the linear relation found for the predominantly magnetospheric emission from more luminous pulsars. This work has been extended with an attempt to separate the thermal vs. non-thermal MSP X-ray luminosities vs. $\dot{E}$ (Grindlay 2005) using data from the 2002 deep dataset on 47Tuc. A more detailed study is nearing completion (Bogdanov et al 2005, in preparation; hereafter BGH05).

A key result, first realized at this Cefalu meeting, is that the eclipsing MSP-W, first located from the HST discovery of its optical companion (Edmonds et al 2002), is remarkably similar to the quiescent low mass X-ray binary (qLMXB) and first-discovered accreting millisecond pulsar, J1808-3658. The deep *Chandra* data showed (Bogdanov, Grindlay and van den Berg 2005; hereafter BGvB05) that its X-ray lightcurve shows broad eclipses of its hard flux but no evidence for the sharp and total eclipse expected for the soft thermal component from the NS (Figure 2a). This can be explained by the system geometry shown in Figure 2b: the MSP wind produces a standing shock at (or near) the L1 point, where mass from the secondary is overflowing the Roche lobe, and non-thermal (synchrotron) emission from this shock is then eclipsed by the secondary at binary phases $\phi \sim$0.4 - 0.6. The longer-rise egress is due to the longer visibility of the

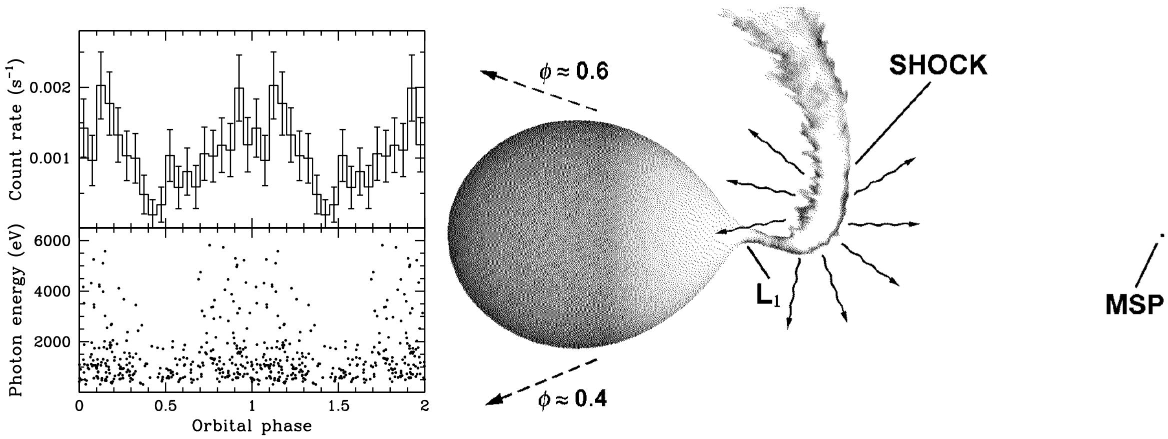

FIGURE 2. *Left:* a) Light curves of MSP-W showing total counts and counts vs. energy folded on the 3.2h binary period. *Right:* b) Sketch of MSP-W to explain eclipse geometry (from BGvB05).

swept-back emission region.

A complete study of the full sample of 19 MSPs with precise locations, now including the new timing positions for MSPs -R and -Y (Freire et al 2005, in preparation), is presented by BGH05 and shows that at least 3 (-W, -J and -O) of the 19 MSPs show significant emission above 2 keV. Certainly for -W, and probably also for the eclipsing systems -J and -O, this is non-thermal (PL) emission from shocked gas excited by the MSP wind. This component for MSP X-ray emission was found (GCH02) to be dominant in the first (and still only) MSP in NGC 6397, N6397-A, which, like that for 47Tuc-W, is probably filling its Roche lobe but not able to accrete. Both have "red straggler" (to red of cluster main sequence) companions, which may indicate mass loss from a sub-giant (N6397-A) or a puffed up envelope for a main sequence star (47Tuc-W). This may be due to the dynamical heating of the companions in their re-exchange. Two of the CVs in NGC 6397 may also have "puffed up" companions given their binary periods vs. inferred companion masses (Taylor et al 2005; hereafter TGE05).

CVs vs. ABs: Distinct spectral variability

Another surprise revealed by the initial 47Tuc observation were the luminosities and spectral hardness of the active binaries. This is extended in the 2002 observation, with ABs making up the largest total population of sources with (likely) optical IDs: extrapolating from the HST coverage used by Edmonds et al (2003) for IDs and extended by HGE05 for initial IDs from 2002 data, the total AB source detections may be as high as 178 vs. 113 for the CVs. Whereas the AB vs. CV X-ray luminosity functions (XLFs) cross at $L_x \sim 10^{30.5}$ erg s^{-1}, with CVs definitely dominant (16:3) for $L_x \gtrsim 10^{31}$ erg s^{-1}, distinguishing these two very different binary populations below this divide is increasingly difficult given the similarly hard spectra (in many cases) and even short-timescale variablity. The latter is revealed by the very similar flare like behaviour of the CV W51 vs. the AB W47, as shown in Fig. 6 of HGE05: both show factor of $\sim$20

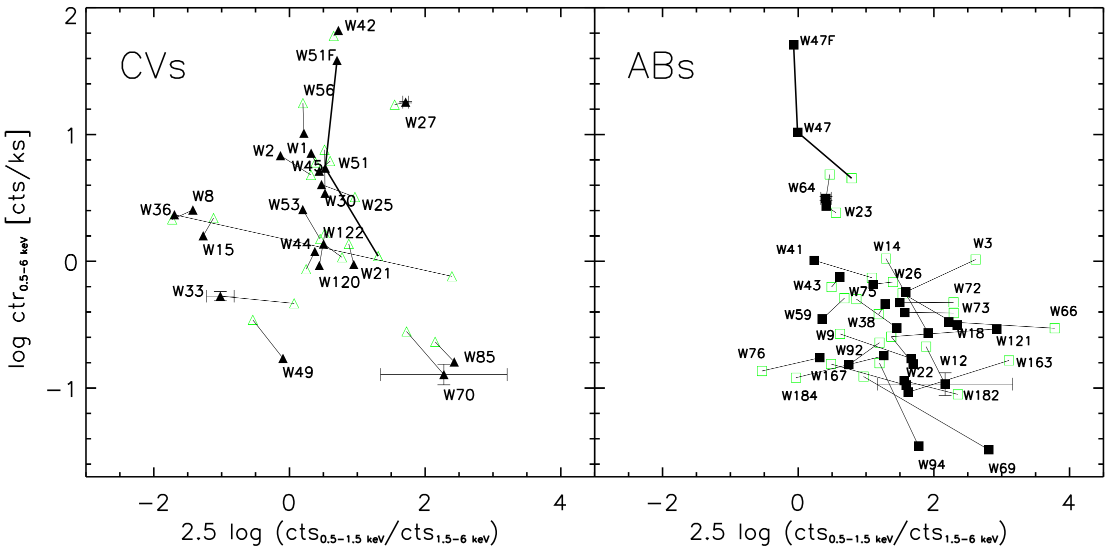

FIGURE 3. X-ray color magnitude diagrams (XCMDs) of *Left:* a) CVs and *Right:* b) ABs in 47Tuc. The 2000 (-I) data (open, green) are connected to the 2002 (-S) data (filled, black) for each source; the large flares for W47 and W51 (*not* removed from the total emission) are connected as a 3rd point ("F").

increases in count rate (0.5-6keV) with rise times ∼30min and durations ∼2-3h. This is perhaps "typical" for very large flares on BY Dra or RS CVn ABs, but is unprecedented for a CV. It is not clear if this is an accretion instability or how rare such giant CV flares are: W51 had two other smaller flares, each with a ∼6×increase and similar timescales, in the third of the four 65ksec obserations in the 2002 data), and only one other CV (W2) had two comparable (∼5×increase) closely-spaced flares out of the lightcurves examined for the 22 optically identified CVs for each of the 4 × 65ksec observations.

The flare spectra, however, are very different and may point the way to distinguish ABs from CVs. The AB flare is very hard (vs. the quiescent spectrum), with a Bremsstrahlung fit yielding kT = 169 ±29 keV and absorption column $N_H = 7 \times 10^{20}$ cm^{-2}vs. a quiescent spectrum (HGE05) with MEKAL fit of kT = 9 ±1.3 keV and $N_H = 11.8 \pm 1.2 \times 10^{20}$ cm^{-2}. In contrast, the remarkable flare (or is it "super-blobby" accretion?) from the CV W51 is fit with (Brems) kT = 3.5 ±1 keV and $N_H = 2 \times 10^{20}$ cm^{-2}, or *softer* than the quiescent emission (HGE05) with (MEKAL) kT = 5.7 ±0.8 keV and $N_H = 4.8 \pm 1.1 \times 10^{20}$ cm^{-2}. Harder spectra are typical of stellar (or solar) flares, where non-thermal processes dominate, whereas an accretion instability and higher $\dot{m}$ for a CV would be expected to be more optically thick and thus softer.

Spectral variability differences for the identified CVs vs. ABs in 47Tuc should be evident in XCMDs for the 2000 vs. 2002 observations (Figure 3). The ACIS-I counts have been transformed to those expected for ACIS-S for the nominal spectra for quiescent emission, taken to be (Brems) kT = 10 keV (CVs) vs. kT = 1 keV (ABs). Comparing sources with at least one of the two measurments $\gtrsim$1ct(0.5-8keV)/ksec for minimal error bars, the 18 CVs show 8:6:4 with positive:negative:uncertain slopes vs. 2:4:0 for the 6 ABs, so the differences are only suggestive.

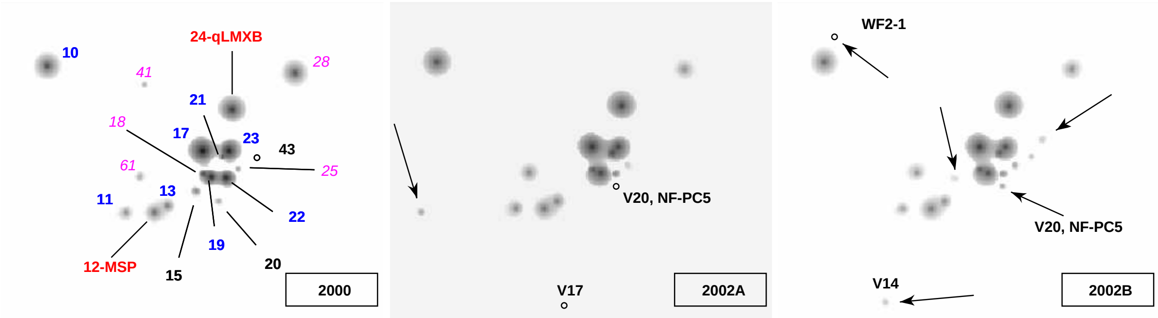

FIGURE 4. *Chandra* images of central region of NGC 6397 from ACIS-I (left; see GHE01b) and -S (middle and right; see GvBB05). Sources are numbered as in GHE01b and new sources are marked. CV source numbers are blue, ABs are black, the MSP and qLMXB are red, and unidentified source *numbers* are magenta. Scale: CVs U17 and U23 are 10.0″ apart. The cluster center is about 1″ from U19/CV2.

VS. NGC 6397

NGC 6397 is the perfect "foil" for 47Tuc: it is core collapsed, with a power law cusp in its core flattening to a core radius with the latest estimate from HST (for main sequence stars) as $r_c = 4.4 \pm 3.2''$ (TGE05) rather than the "perfect" King model with $r_c = 24''$ for 47Tuc. Given the factor of $\sim$2 closer distance of NGG 6397 (2.3kpc), the isothermal core is $\sim 8\times$smaller in radius than that for 47Tuc and thus for the quoted stellar luminosity density (log ρ_L $\sim$5.68 vs. 4.81 for 47Tuc) has a core mass (and IXB factory) some $\sim 400\times$smaller than that of 47 Tuc. It is metal-poor ([Fe/H] = -2.0 vs. -0.7 for 47Tuc) and has absolute magnitude -6.63 vs. -9.42 for 47Tuc, suggesting a mass ratio of 13 for constant M/L. Thus it provides a contrast in its dynamical history, metallicity and mass.

Our initial 50 ksec observation of NGC 6397 with ACIS-I in July 2000 (Grindlay et al 2001b; hereafter GHE01b) was followed up with a comparable exposure (2×25 ksec) with ACIS-S on May 13 and 15, 2002. Details are reported in Grindlay et al (2005; hereafter GvBB05); highlights for comparison with 47Tuc are reported here. The Wavdetect images of the ACIS-I vs. -S exposures are shown in Figure 4. In the core region shown, sources U15, U20 and U41 are detected only in the ACIS-I observation and 6 new sources (marked with arrows) are detected in one or both of the -S exposures. The Vxx designations mark identifications with variable stars in the cluster reported by Kaluzny and Thompson (2003) and references therein. Open circles mark lower-threshold detections with one either an AB (V20) or possibly a "non-flickerer" (NF-PC5; a probable He WD, see Taylor et al 2001) – both are within the 95% confidence radius ($\sim 0.5''$). Additional source details and identifications with HST stars are given in GvBB05 and TGE05. Additional sources of note are outside the field shown (e.g. U60, recently identified with HST by TGE05 as the 9th CV, is along the U24 - U12 line to the SE). Source U28, tentatively classified as a CV by GHE01b from its hard spectrum, is in fact identified by Cool et al (in preparation) as a background edge-on Seyfert galaxy(!) so that the cluster CV total from HST/WFPC2 identifications (TGE05) remains at 9.

Clearly many sources are highly variable. U22 = CV5 decreased its X-ray luminosity by a factor of $\sim$10 and the ABs show large variations. The XCMD for the ACIS-I

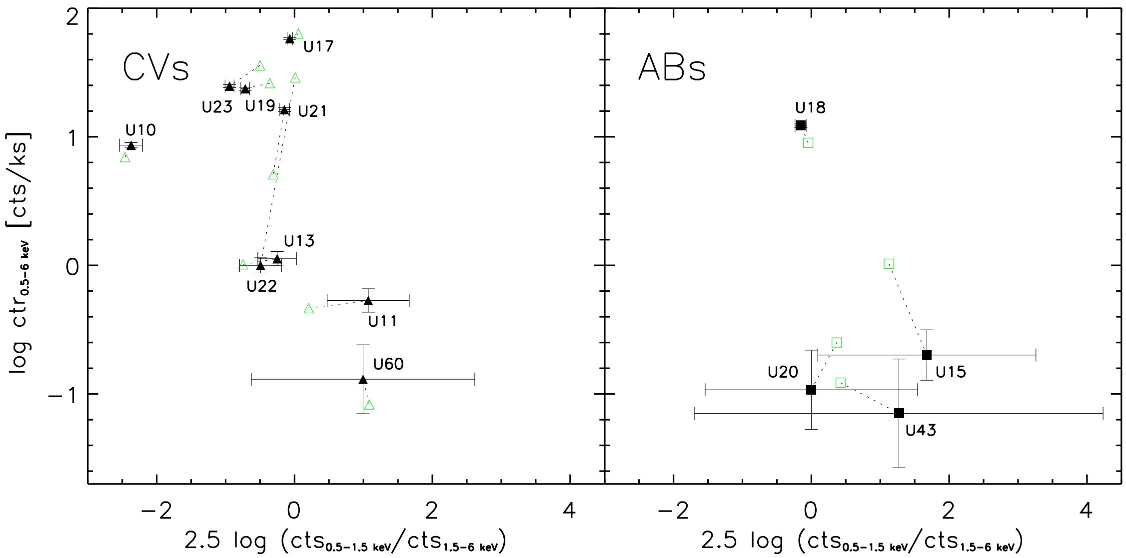

FIGURE 5. X-ray color magnitude diagrams (XCMDs) of *Left:* a) confirmed CVs and *Right:* b) candidate ABs in NGC 6397. Colors and labels for the 2000 vs. 2002 data are as in Fig. 3.

vs. -S spectral variability of the CVs and HST-identified (TGE05) CVs is shown in Figure 5 for comparison with the 47Tuc plot (Fig. 3). Although there are fewer objects, the CVs now all show brighter-softer variations and the ABs (with larger errors) are again brighter-harder. All four CVs (CV1/U23, CV2/U19, CV4/U21 and CV6/U10) with binary periods discovered with HST (TGE05) show significant modulation in the combined *Chandra* data; details are discused by GvBB05.

DO IXBS TRACE CLUSTER FORMATION AND EVOLUTION?

The IXB populations and spatial distributions in both clusters can be compared for constraints on compact object populations and IXB formation/evolution. First, since the CVs and qLMXB/MSP systems are both significantly over-produced, by factors of $\gtrsim$10, in these clusters vs. the field populations (see GvBB05), both are produced in exchange encounters (primarily) with primordial binaries or, particularly during core collapse for NGC 6397, by tidal capture. NSs are more concentrated in the core and thus favored in IXB production, and lower mass WDs may be more easily expelled than NSs in the core collapse that has occurred in NGC 6397. Thus if both clusters have the same initial mass functions (IMFs) and thus ultimately ratios of white dwarfs (WDs) to neutron stars (NSs), the ratios of IXBs containing each should be similar in both clusters, with perhaps more NS-IXBs expected in NGC 6397.

TABLE 1. Comparison IXB counts: 47Tuc vs. NGC 6397

	Source Type	47Tuc	NGC 6397
Observed:	qLMXBs (NSs)	5	1
	MSPs (NSs)	$\sim$30*	$\sim$2
	CVs (WDs)	$\sim$30	$\sim$12
	NSs/WDs in IXBs	$\sim$1	$\sim$0.25
Derived:	Γ_c (rel. coll. rate)	$\sim$3	$\sim$0.3
	M_{GC} (rel. total mass)	$\sim$13	$\sim$1
	(NS/WD) / (Γ_c/M_{GC})	$\sim$5	$\sim$0.8

* MSP and CV numbers for both clusters are estimated totals

NSs vs. WDs in IXBs: cluster IMF?

In fact, as we originally suspected (GHE01b), the relative numbers of WDs vs. NSs locked up in IXBs in 47Tuc vs. NGC 6397 are surely not the same. In Table 1 we summarize the observed IXBs for both clusters and derive the ratio of expected IXBs containing WDs vs. NSs *normalized* by the ratio of relative collision number, or rate of IXB production, per unit cluster mass. The scaling for collision number, in a cluster core with density ρ_c and core radius r_c is $\Gamma_c \propto \rho_c^{1.5}\ r_c\ ^2$, is taken from Verbunt (2003) and Heinke et al (2003). The bottom line is that the NS/WD ratio in IXB systems appears to be enhanced by a factor of $\sim$6 in 47Tuc vs. NGC 6397. It is conceivable that the core collapse in NGC 6397 would favor production of WD-IXBs by tidal capture simply because WDs are so much more numerous than NSs in any cluster. However binary "burning" to halt core collapse presumably produces a net loss of binaries in the core (and indeed the ABs appear in Figure 4 to be relatively deficient near the cluster center and have a core radius measured (TGE05) to be significantly larger (r_c = 9.3$\pm$3.5$''$) than the CVs (r_c = 1.0$\pm$3.5/arcsec). If the NS/WD ratio difference is due to CV production in core collapse, then the youngest cluster CVs should be in the central core. It is interesting that the three optically faintest CVs (7, 8 and 9 = U11, U13, and U60), all with absolute magnitudes Mv $\sim$11.5 - 12 and companion masses thus $\sim 0.1 M_\odot$ (TGE05) are indeed farther out from the cluster center as expected if CVs 1-6 were more recently created.

If CV (vs. LMXB) production is not favored in core collapse, then the lower NS/WD ratio in NGC 6397 points to the underlying NS population being deficient. This could be (partly) due to the lower escape velocity for its reduced cluster mass, but the present mass may be greatly reduced by tidal stripping and so the initial masses are obviously uncertain. More likely, the large metallicity difference suggests a much flatter IMF for 47Tuc and thus NS initial production, as originally suggested by Grindlay (1987) for the luminous galactic globular cluster LMXBs and as now suggested for the pronounced metallicity dependence of extragalactic cluster LMXBs (e.g., Jordan et al 2004).

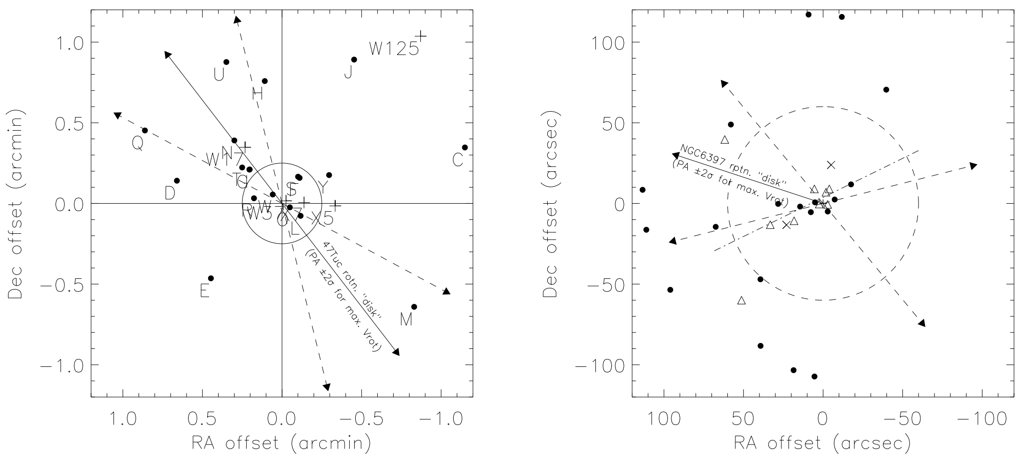

FIGURE 6. IXB sources locations vs. cluster rotation equator for *Left:* a) MSPs (filled dots) and qLMXBs (+) in 47Tuc; circle marks optical core radius, and *Right:* b) all sources in NGC 6397: triangles=CVs, X=MSP and qLMXB, and filled dots= ABs and unIDs. The source "equatorial" plane is fit with the dot-dashed line for sources inside the circle; exterior sources are increasingly background objects.

Interacting binaries vs. cluster rotation?

As noted in GHE01b and as now even more apparent in Figure 4, the IXBs in NGC 6397 appear possibly anisotropic: at radii $\lesssim 1'$ from the cluster center they are predominantly scattered along a NW-SE "line" which is matched by the "line" of 5-6 luminous blue stragglers in the core. With more sources (mostly ABs) now detected in the cluster (Figure 4), this trend is strengthened (e.g. 5 of the 6 "new" sources are roughly along this axis). Very similar cluster core flattening of the *Chandra* source distributions are apparent for the globulars NGC 6440 and NGC 6266 presented by Pooley et al (2002). 47Tuc also shows an apparent anisotropy of its NS-IXBs (MSPs and qLMXBs), as shown by Grindlay (2005) who examined correlations with the cluster proper motion.

A better (or more plausible) possible interpretation, if any of these anisotropies are significant (and simulations are planned) is to consider cluster rotation. Kim, Lee and Spurzem (2004) have found that core collapse and mass segregation are enhanced by cluster rotation. In Figure 6 the NS-IXBs for 47Tuc and the complete IXB sample for NGC 6397 are shown with the cluster rotation equator directions ($\pm 2\sigma$) from the rotation measurements of Gephardt et al (1995) marked. For 47Tuc, the bulk of the MSPs and qLMXBs are within the $\pm 2\sigma$ region around the rotational equator, and for NGC 6397 the flattened core region is at $\sim 2.5\sigma$ from the rotation equator line (but also, given the large uncertainties, $\sim 2.5\sigma$ from the rotation axis!). The position angle (PA) of the rotation velocity equator for NGC 6397 is very uncertain and only measured in integrated light; for 47Tuc the PA is in excellent agreement for both integrated light and individual stellar velocities. Large stellar velocity samples are needed to measure the stellar rotation for NGC 6397 (and NGC 6440 and NGC 6266) to test these alignments.

For 47Tuc, the implication of alignment of the NS-IXBs could be that the NSs, as the oldest objects in the cluster and which may have formed in the proto-cluster disk, have

retained their mean angular orbital momentum despite having acquired companions in exchange collisions. Angular momentum alignment would remain fixed in the cluster frame, which was not necessarily the case for anisotropies induced by the cluster proper motion (Grindlay 2005). For NGC 6397, the most natural expectation is that rotational flattening during core collapse has scattered IXBs preferentially in the equatorial plane.

CONCLUSIONS

Interacting binaries in globular clusters are allowing new domains of stellar and binary evolution to be studied: from clues to the formation of the very first massive stars (and NSs), to the oldest and least luminous CVs to the extremes of stellar binaries. They point the way to new dynamical phenomena, including re-re-cycling and alignment processes with cluster angular momentum. High resolution *Chandra* imaging has provided the key for new understanding and new questions.

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